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PROFILES OF TRANSPORT, CURRENT AND TEMPERATURE IN THE MODE AREAS OF THE NORTH ATLANTIC

by
T. E. Pochapsky and F. D. Malone

July 1975

TECHNICAL REPORT No. 2
CU-2-75
Office of Naval Research
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Project No. NR 083-243

and

TECHNICAL REPORT No. 1
CU-1-75
National Science Foundation
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ABSTRACT

Measurements of the transport and temperature as a function of depth were obtained at two locations in the North Atlantic during the MODE experiments of the IDOE. Vertical profiles of the current as well as hodographs were determined from these. Acoustic ranging was used for the flow measurements based on techniques developed in the instrumented float program of the senior author. The results of these measurements are presented in graphical form for experiments at 28°N, 68.7°W during a 4-day operation in 1972 and at 27.9°N, 69.7°W for a 11-day sequence in 1973. Profiling drops are described individually along with experimental or analytical factors affecting specific profiles. This report is a distillation of the measurements only and avoids interpretations of their significance.

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INTRODUCTION

Past measurements obtained at clusters of neutrally-buoyant floats have shown that oceanic current and temperature gradients are pronounced over distances of tens of meters even in the deepest waters (Pochapsky, 1972). It should be noted that measurements with floats are quasi-Lagrangian in that the clusters tend to follow a given volume of water and temporal changes are not subject to the inclusion of Doppler frequencies produced by a mean flow at anchored installations. Further measurements were needed to determine the vertical wave numbers and amplitudes associated with these variations. The cluster procedure offered a method of obtaining such data. In this, slave floats of a cluster are anchored close to the sea floor so as to form an array of transponders while an interrogating master float is made to sink through the entire vertical oceanic column into that array while communicating with individual transponders. It rises, continuing its interrogations, after resting on the bottom or hovering at a preset depth for a desired length of time. Profiling measurements of this nature are approximately Eulerian rather than Lagrangian. Interrogations are heard at the ship where they are recorded and stored for future processing.

The opportunity to perform such measurements in connection with the Atlantic Mid-Ocean Dynamics Experiment or MODE of IDOE during 1972-73 was welcomed because results could be related to the measurements of other investigators. An objective then was to obtain repeated vertical profiles to the sea floor of the current by acoustic ranging along with temperature profiles in two geographical areas, and, in addition, to measure the manner in which the current and temperature change with time in a few instances where the profiling master is set to hover at specific depths rather than to sink to the sea floor. A second purpose was to investigate experimental features, including limitations of this method of measurement. This report presents in graphical forms the results of these varied measurements, including 1) horizontal trajectories of the profiling float which serve as measures of the rate of water transport as a function of depth, 2) profiles of the N-S and E-W components of the horizontal current as derived from the transport, 3) hodographs of the horizontal current as a function of depth, and 4) temperature changes with depth in the kilometer of water just over the sea floor. Because the profiling system is also under study, measurements are presented in a variety of filtered forms so that the limitations to the accuracy can be appreciated better. All flow features pertaining to a specific drop will be summarized on a single sheet for that drop; any comments will tend to be on features of the measurements rather than on the significance of the results. Deep temperature profiles, similarly, are all shown in a single sheet in order to facilitate comparisons.

Analyses will be presented elsewhere (Pochapsky, 1975a)

PROCEDURE

Features of the instrumented floats have been described in previous publications (Pochapsky, 1961). Characteristics of the instrumentation as used in these experiments and in previous float work, as well as methods used to convert telemetered times into physical parameters are described in a separate report (Pochapsky, 1975b). A brief description of the profiling procedure, however, is given here as necessary to facilitate interpretation of the results.

Either a hovering or a profiling float transmits acoustic ping doublets every 12 sec and the first of these pings trips two transponders which are secured near the sea floor. The coded responses of the transponders are heard and repeated by the free float. All acoustic transmissions from the profiling float are recorded at a monitoring ship. The two pings of a doublet are separated by a time which is proportional to the temperature or pressure present at the free float. That time can be measured at the ship to a resolution of 1 part in 5000 of full scale, or to 0.1 ms The time between the first ping of a doublet and the transponder response as heard at the profiling float is a measure of the distance between the transponder and float. The resolution in time of the distance allows a 10 cm resolution in distance but ship motion prevents better than a 1 m resolution in the present experiments. Measuring-system noise in the velocity determination is reduced to an estimated ± 1/2 cm $\sec^{-1}$ by filtering out changes which occur over vertical scales shorter than approximately 100 m in wavelength. The error increases as that scale is reduced. The wavenumber at the cut-off of the filter depends on a number of experimental factors and, for example, will vary within an individual profile as the speed of descent changes. The appropriate length at cut-off in specific sections of profile, however, can be estimated by noting the highest wavenumbers present.

The primary measurement obtained in profiling is a sequence of radial distances between a free float and two bottomed transponders spaced approximately 7 km apart. These distances together with the float height above the sea floor determine the horizontal path of the free float as a function of time while the horizontal current is obtained by differentiating the horizontal displacement with respect to time. When the float moves vertically at a constant speed, the leading point of the horizontal trajectory at any depth is such that the vector distance between it and the initial surface point is proportional to the rate of flow of all water layered between the surface and that depth. Consequently, the basic data obtained in the acoustic scheme is of net transport as a function of depth. As noted earlier, the accuracy of the velocity determinations is diminished as the vertical resolution is increased; conversely, the accuracy increases as velocity means are taken over larger distances, so that accurate averages can be obtained over large depth intervals even when there are large gaps in the data. Within limits, the accuracy is proportional to the wavenumber.

1. Location and schedule.

Two different field operations were carried out. In one, designated here as M-0 to identify it as part of the MODE-0 operation, 5 profiling drops were made during the period 23 to 27 August 1972 at a location where the southern transponder was at 28°00'N, 68°39.5'W. In the second area during MODE-1, designated here as M-1, 11 drops were made during the period 6 to 17 June 1973 with the southern transponder at 27°50.5'N, 69°41.2W. The latter was on a bearing of 190° and range of 17 km from the Central Mooring of the current meter array used in the MODE-1 operations. Most of the M-1 drops were made at a distance 14 km south of that mooring which was heavily instrumented with current meters and other instrumentation of the IDOE program. The first four drops were made 7 km south of the mooring in the expectation that results could be compared more closely with measurements made on the mooring. To our surprise, the mooring had its own transponder which communicated freely and erratically with our interrogating float and invalidated the multiplexing scheme. Some useful data was obtained but a move farther to the south was required in order to obtain complete profiles. Details of the transponder separations, drop times, etc., are presented in Table I. A map showing drop positions within the arrays is presented in Fig. 1.

REVIEW OF PROFILING DROPS AND EXPERIMENTAL FEATURES

Experimental features are described in the following when they are appropriate to specific drops. Because most such features are covered in the brief MODE-0 section, that section also serves to provide a general description of experimental aspects. Each drop is listed under its own heading in the following paragraphs.

1. MODE-0

Drop 2, Fig. 2.

A magnesium link to the sinking weight dissolved prematurely during the descent and so the float started its ascent at a depth of 4500 m. The 1-min down plot in Fig. 2 uses points which are averaged in 1-min time slots,—there are approximately 5 data points per slot. The profiling float descended at a typical speed of 20 m min^{-1}.

The designation 27Δ on a profile indicates the results of passing data through a low-pass, 5-step, triangular filter; 1-min data averages are used as input but velocities are based on 3-min time steps. Specifically, if A, B, C, D, E, F, G, H, ... is a sequence of 1-min averaged horizontal distances, the filtered velocity is given by the expression

Table 1. Profiling drop times and locations

Drop number	Day	Time start (GMT)	Descent time, (hr)	Ascent start,[3] (hr)	Rise time, (hr)	Location from southern transponder (km)
	Aug. 1972					
M-O[1], 1	23	14:43	0.39p	15:07	0.28	1.5N, 0.5W
2	23	16:07	3.28p	15:23	—	0.8N, 0.7W
3	24	17:35	4.92	36:33	3.23	3.1N, 1.6W
4	25	17:47	4.93	—	—	2.9N, 2.4W
5	26	17:23	4.77	—	—	2.2N, 2.7E
	June 1973					
M-1[2], 1	6	23:13	3.92	35:48	2.53	8.7N, 0.9W
2	7	19:46	4.30	—	—	13.4N, 1.9W
3	8	17:46	7.07h	36:09	—	11.2N, 2.9E
4	9	23:08	6.33	39:26	2.76	7.4N, 3.6E
5	11	00:16	leak	—	—	3.4N, 3.6E
6	11	22:15	6.38	—	—	2.9N, 3.7E

(Continued from previous sheet)

7	12	21:04	5.25	34:56	2.65	1.9N, 3.3W
8	13	19:12	7.68	37:18	2.63	2.8N. 1.8E
9	14	18:32	8.80h	36:56	2.73	3.0N, 2.0E
10	15	18:51	3.66	36:54	2.71	3.1N, 3.0E
11	16	20:41	6.57h	35:08	1.23	3.2N, 1.3W

p, premature rise; h, hover

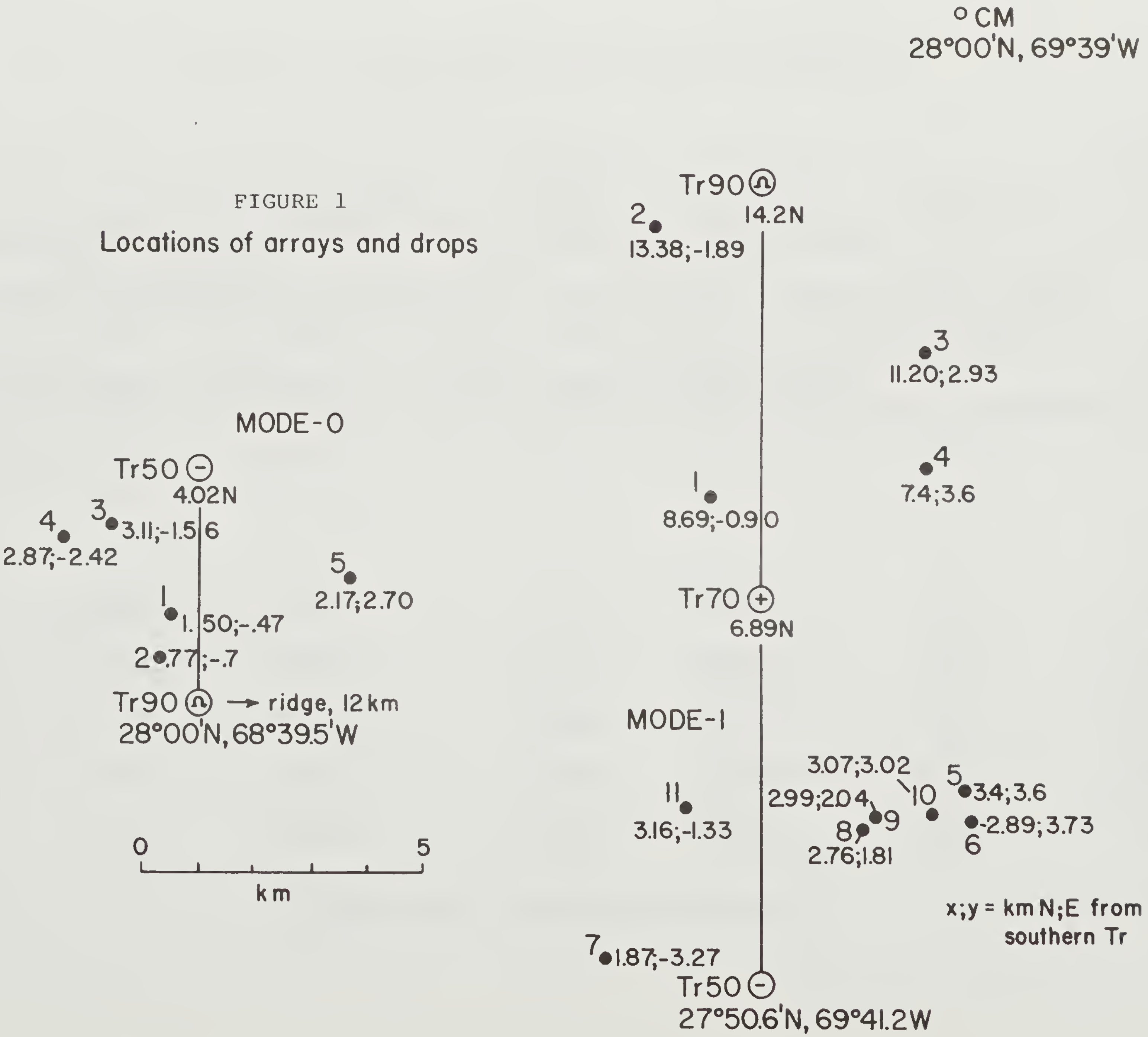
[1] MODE-0 location. August 1972. Southern transponder at 28°00'N, 68°39.5'W. Transponder separation, 4.02 km. Water depth, 5300m.

[2] MODE-1 location. June 1973. Southern transponder at 27°51'N, 69°41'W. Other transponders to north 6.89 and 14.20 km. Water depth, 5450m.

[3] Measured with reference to the day the profile was started.

FIGURE 1

Locations of arrays and drops



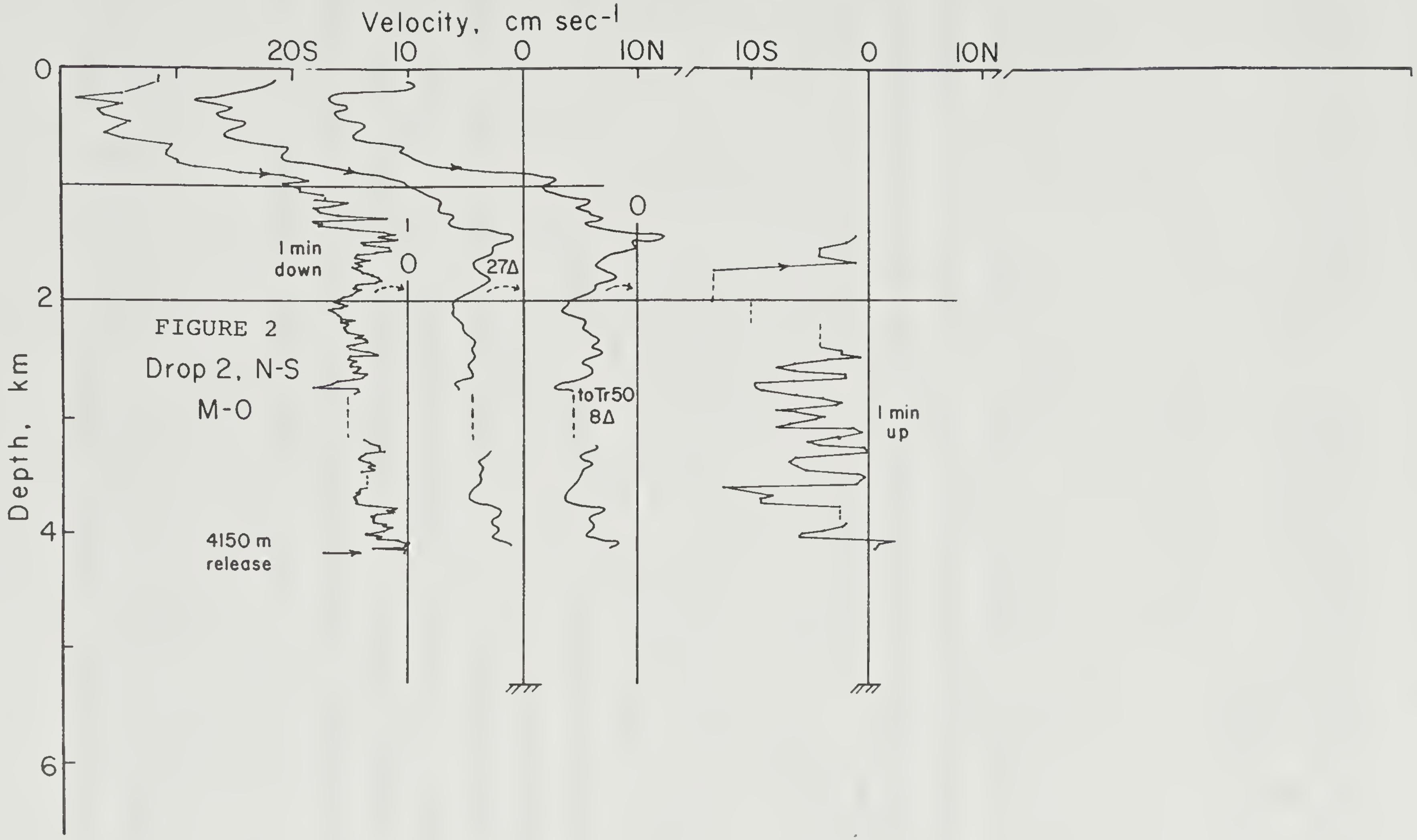


FIGURE 2
Drop 2, N-S
M-O

$$\frac{1}{9\Delta}\ [(F-C) + \frac{2}{3}(E-B+G-D) + \frac{1}{3}(D-A+H-E)]$$

where Δ is approximately 60 sec. A somewhat narrower filter, or 8Δ filter, is sometimes used and this is obtained from the formula

$$\frac{1}{4\Delta}\ [(B-D) + \frac{1}{2}(A-C + C-E)]$$

The 1-min data for this drop are unusually good, probably because there was a glassy sea. The resolution of all profiling suffers because acoustic transmissions were recorded on a bouncing ship rather than at the profiling float itself. For example, when the hydrophone on the ship moves to ± 1 m extremes at 1-min intervals, the error expected is 3 cm sec^{-1} from 200 cm/ 60 sec. Filtering is done to reduce such errors to approximately ± 1/2 cm sec^{-1}.

The profile labelled Tr 50 shows the current in the direction of Transponder 50 as derived solely from transmissions to that transponder and after use of the 8Δ filter. The direction to the transponder is not far from N-S and, as expected, the profile is similar to that resolved in the N-S direction from transmissions to two transponders.

The results obtained during ascent are suspicious and must include spurious movements of the rising float. Such gyrating motions may be caused by a deflecting action induced by the whip antenna which probes forward into the vertical ascending motion.

A vertical dashed line is used on all figures to represent data gaps and to mark the average velocity between the upper and lower depths terminating such a line.

Drop 3, Fig. 3.

Current profiles for this drop, down and up, are determined with a 27Δ filter. The up profiles are not erratic as in drop 2 and variations tend to be out of phase with those obtained on the way down. The time difference between ascent and descent at middepths is 18 hrs and so both inertial and tidal flows could contribute to the current variations.

The horizontal trajectories, or plan views, of the float paths during descent and ascent are adjusted to represent results for a constant profiling speed of 35 cm sec^{-1}. All horizontal trajectories in this report are normalized to this rate of traverse of the ocean column. Depths are marked in km along trajectories. In this drop, the horizontal paths during descent and ascent are similar to one another below the main thermocline but they diverge in shape above a depth of 500 m where there is a 6 cm sec^{-1} difference in E-W velocity. At a depth of 500 m the ascent and descent times differed by 21.5 hr or almost a full day.

Either the total rate of transport or the average current can be obtained from the trajectories by use of the inset scale of Fig. 3 marked "cm sec^{-1}/ 100 m". When the distance moved between any two depths is measured in terms of this scale, the result is a measure of the average velocity times the depth difference or of the net rate of horizontal transport between the two depths in units of 10^4 cm^3 sec^{-1} through a 1-cm wide vertical section between those depths. The flow through a 1-m wide section would have the same measure if expressed in units of 10^6 cm^3 sec^{-1}, or 1 m^3 sec^{-1} per scale unit. Thus, the scaled distance allows determining directly the net transport in cubic meters per second across a meter wide column between the two depths.

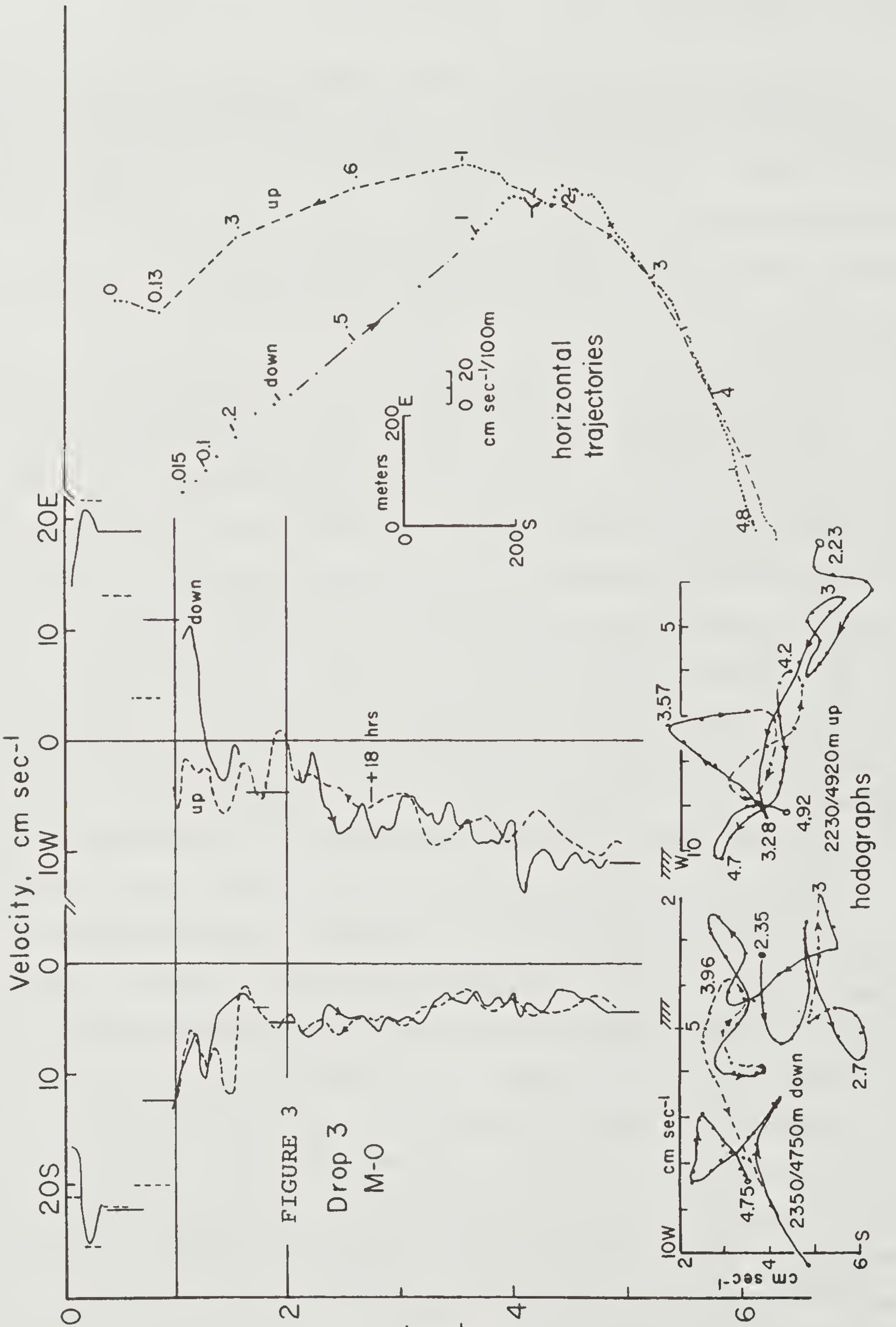


FIGURE 3

Drop 3
M-0

As an example, the scaled distance between the depths of 2 and 4 km is 150 scale units. Then, 150 m^3 sec^{-1} of flow takes place through a 1-m wide column of water between those depths. A horizontal flow of 150 x 10^4 cm^3 sec^{-1} occurs through a 1-cm width in this column 2 x 10^5 cm long and so the average velocity is 7.5 cm sec^{-1}, a value consistent with magnitudes shown on the velocity profiles. The direction shown on the trajectory during descent is to the southwest. The ascending trajectory is always reflected on the axes when drawn so that it shows the same trends as occur during descent.

Hodographs of the horizontal currents on descent and ascent below the thermocline are also illustrated in Fig. 3. These show the course of the tip of the velocity vector as a function of depth. Depths, in km, are marked along such curves. For example, during descent below a depth of 2.35 km where the velocity is 3.1 cm sec^{-1} west and 3.6 cm sec^{-1} south, the velocity goes through a series of fluctuations and a steady drift to a velocity of 8.5 cm sec^{-1} west and 3.6 cm sec^{-1} south at a depth of 4.75 km. The origin of the velocity vector is not shown explicitly; it lies off scale and would appear on the drawing near the bottom of the E-W velocity profiles. Hodographs illustrate the nature of the changes with depth of the current vector better than do the separate velocity component profiles.

Drop 4. Fig. 4.

Sonic transmission was poor during this drop and so the vertical resolution suffers. Nevertheless, good average currents were obtained over vertical distances of a few hundred meters. The shape of the horizontal trajectory is not as vulnerable to the accuracy or loss of data as is the velocity which is obtained after differentiation of such data.

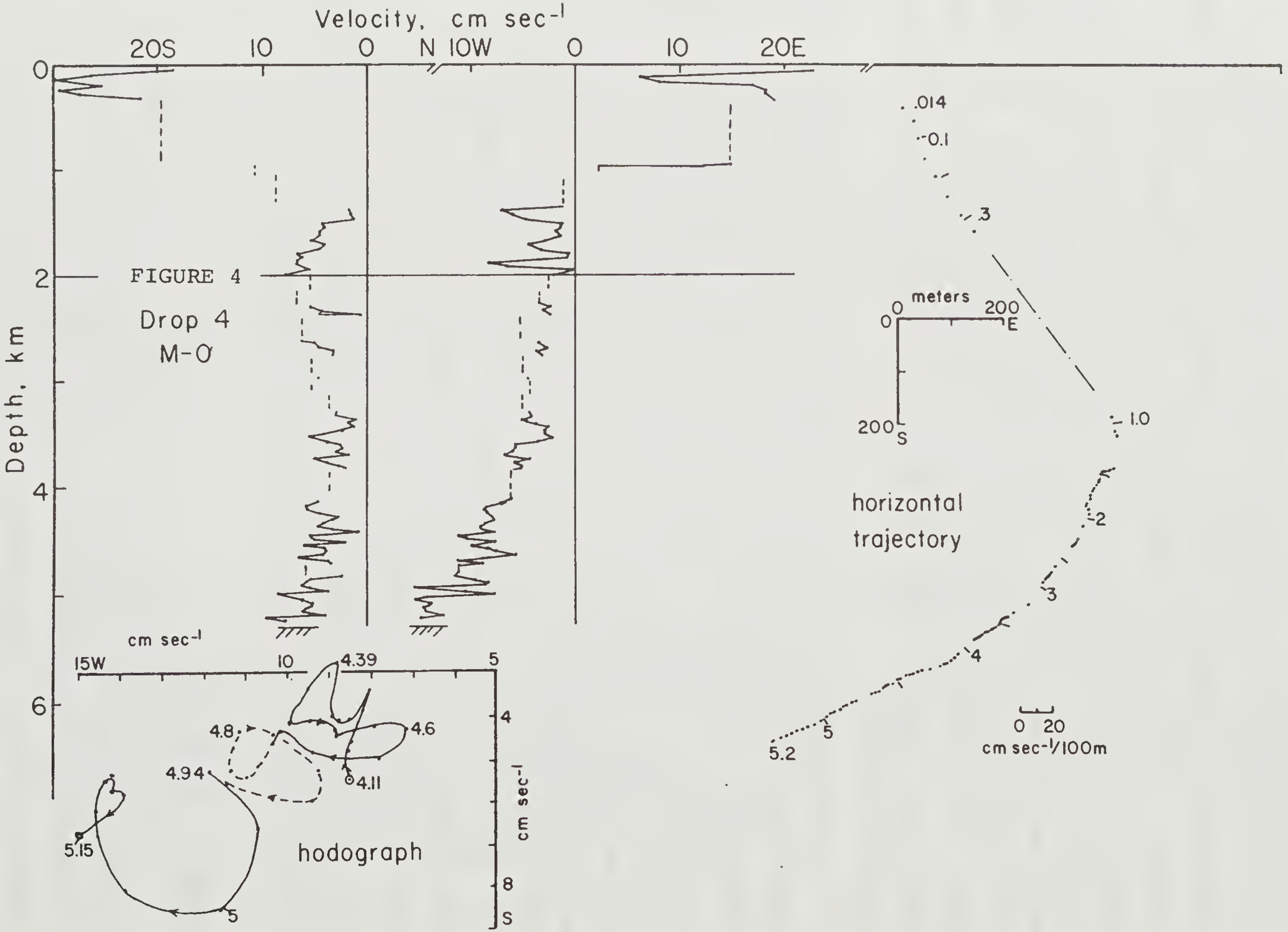


FIGURE 4

Drop 4

M-O

Drop 5. Fig. 5.

Drop 5 was made at a position favorable with respect to the transponders in that errors in the telemetered times are not magnified appreciably by trigonometric factors during computation of the horizontal components of current. The 1-min-averaged velocities are "hashy" and this is most likely the result of ship motions. We note that ship heaving actions take place at periods which are approximately one half the telemetering repetition time of 12 sec. As noted before, filtering should remove most of this ship-motion induced error.

The error remaining after filtering can be estimated in terms of a spectrum analogue. In a digital filter, the high wavenumber data is folded into lower wave numbers and such aliasing, as a first approximation, is assumed to contribute a spurious constant displacement-power density at all lower frequencies. But the filters used pass only wavenumbers at least 4 times smaller than those appropriate to the 1-min, 15-25 m, sampling lengths and so only 1/2 the high-frequency displacement noise passes through that filter. This follows because approximately 1/4 the net "power" leaks into the smaller wavenumbers and this means 1/2 the displacement amplitude. Another factor of 1/3 is achieved when the displacement spectrum is converted into a velocity spectrum ("unwhitening") because the time interval is changed from 1 to 3 minutes. The net maximum contamination expected on this basis is 1/6 of $\pm$ 3 cm sec^{-1} or $\pm$ 1/2 cm sec^{-1}. The fine structure of the 27Δ filtered curves of Fig. 5 lies in this range and so may be, at least in part, caused by transmission noise. Recording at the profiling float instead of at the ship would bring about an important reduction in such reception noise and so would probably make the

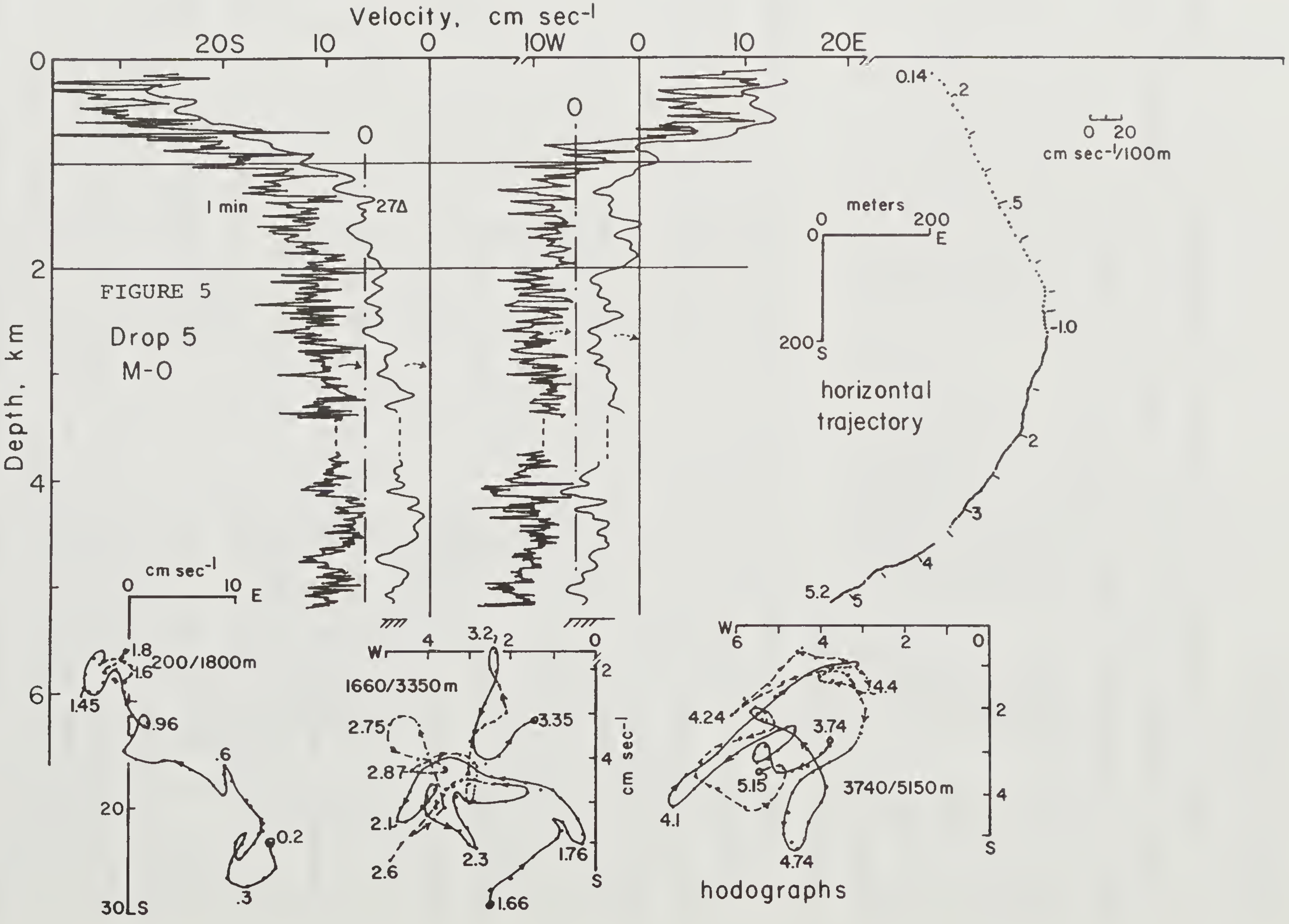


FIGURE 5

Drop 5
M-O

use of filters unnecessary.

2. MODE-1

Drop 1, Fig. 6.

Drop 1 of MODE-1 was made at a location which was too close to Transponder 70 to obtain accurate E-W determinations. The N-S velocities, however, are off high accuracy. Fluctuations at large wavenumbers in the E-W profile which have amplitudes appreciably greater than those in the N-S profile are probably of instrumental origin and caused by a magnification of the errors in measuring transponder distances which occurs when a resolution is made in the E-W direction.

The down and up profiles were obtained almost a half day apart and show an out-of-phaseness which can be expected for inertia currents or diurnal internal tides. Past work with float clusters suggests that the changes are of inertial rather than tidal origin. At a depth of 3000 m, profiles were separated in time by 11 hrs. Gaps in the data, particularly through the 1000-2000 m depth interval, resulted when a foreign transponder on the nearby MODE Central Mooring, CM in Fig. 1, started to communicate in an erratic fashion with the profiling float and this upset the multiplexing cycling.

Drop 2, Fig. 7.

Interference from the acoustic instrumentation of the Central Mooring was more serious during this experiment than in the previous one and data was obtained only in waters below middepths.

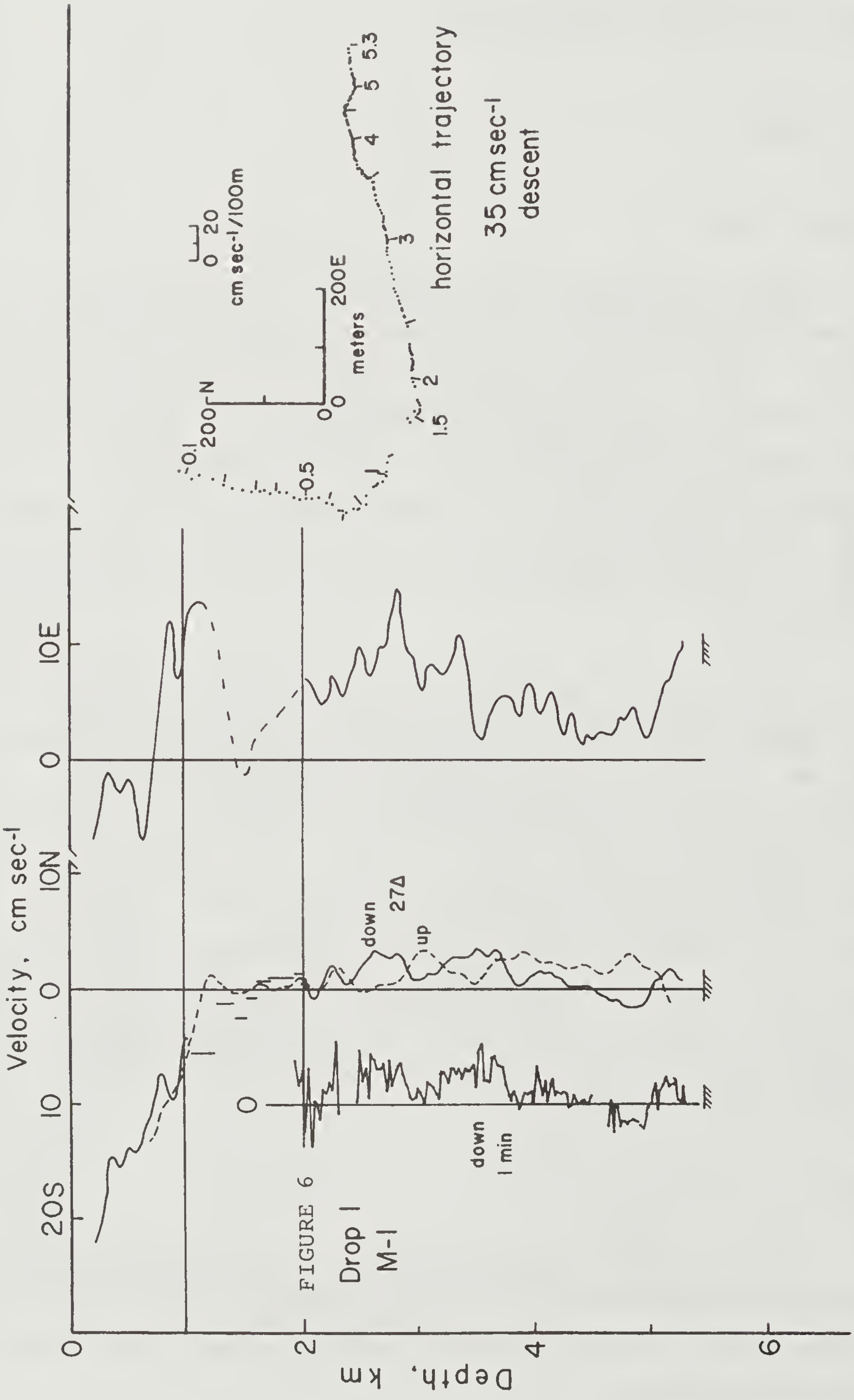


FIGURE 6
Drop 1
M-1

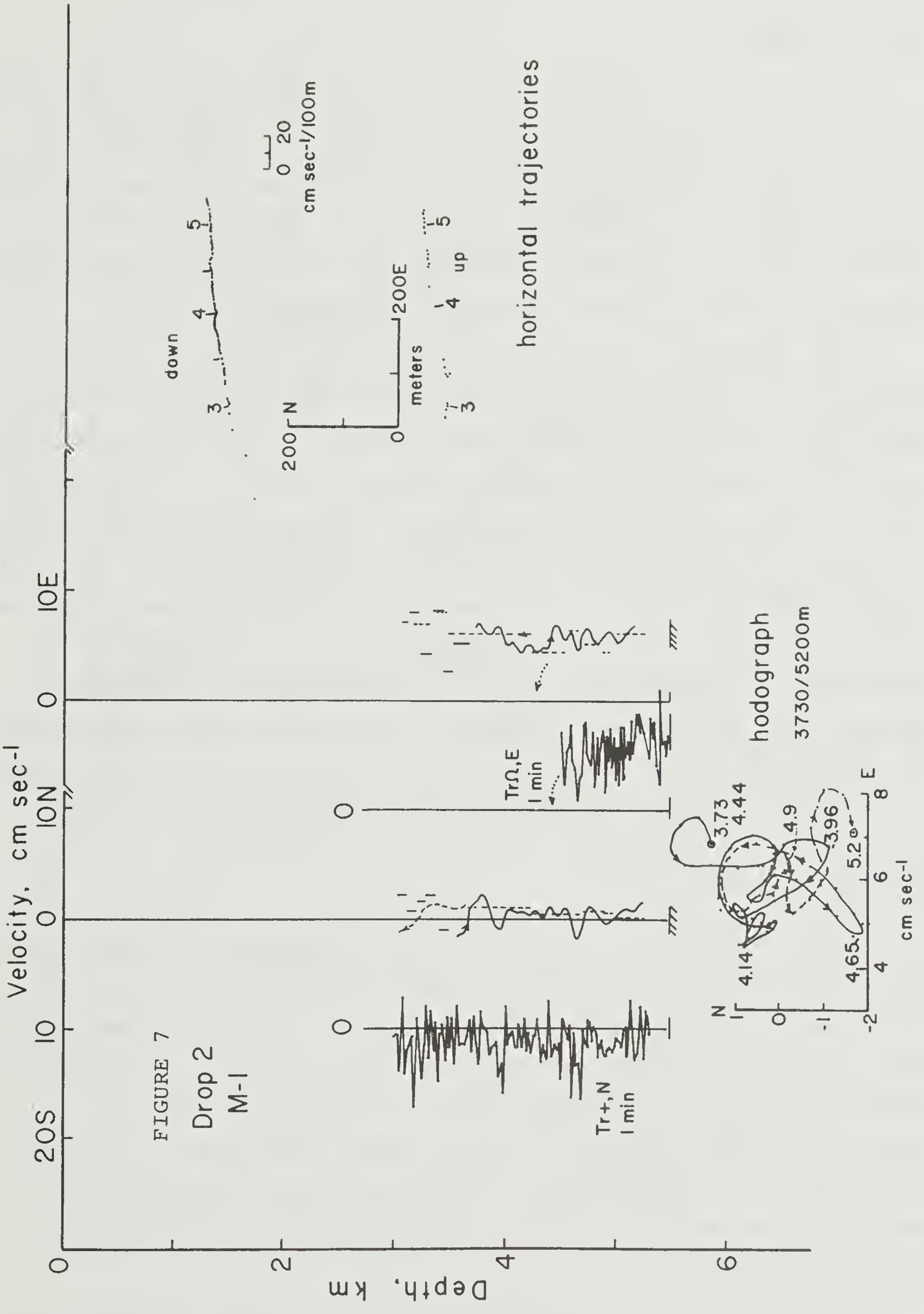


FIGURE 7

Drop 2

M-1

Drop 3, Fig. 8.

Drop 3 was placed well relative to the array and interference from the extraneous transponder was less than in the previous drop. This profile is unusual in that the profiling float was trimmed to hover at a depth of 3800 m rather than to go to the bottom. Data acquired during hovering will be reported elsewhere (Pochapsky, 1975b).

The unusually large amplitudes at relatively high wavenumbers of the current variations obtained during descent are troubling. They exist both in the high-resolution 1-min E-W results and in the filtered results. They also exist in the communications with a single transponder and so are not caused by a trigonometric magnification of errors during computations. These motions were definitely carried out by the float but seem more likely to be caused by a spiralling descent in a gently rifled motion of the float rather than by internal waves. The velocity of descent was 19 cm sec^{-1} and the horizontal variations are in the range $\pm$ 2 cm sec^{-1}. The associated Reynolds number is 57,000.

Drop 4, Fig. 9.

Even though this drop was placed slightly farther from the alien transponder than were the previous ones, that transponder continued to interfere in an unpredictable manner. The effect was serious and data for the N-S component was lost from the surface down to a depth of 2200 m. On the way up, Transponder 70 was almost due west of the profiler and so transmissions to it alone are accepted as yielding the easterly motions, illustrated as the dashed velocity profile.

Although few positions on the way up were judged suitable for determining velocities, the positions that were

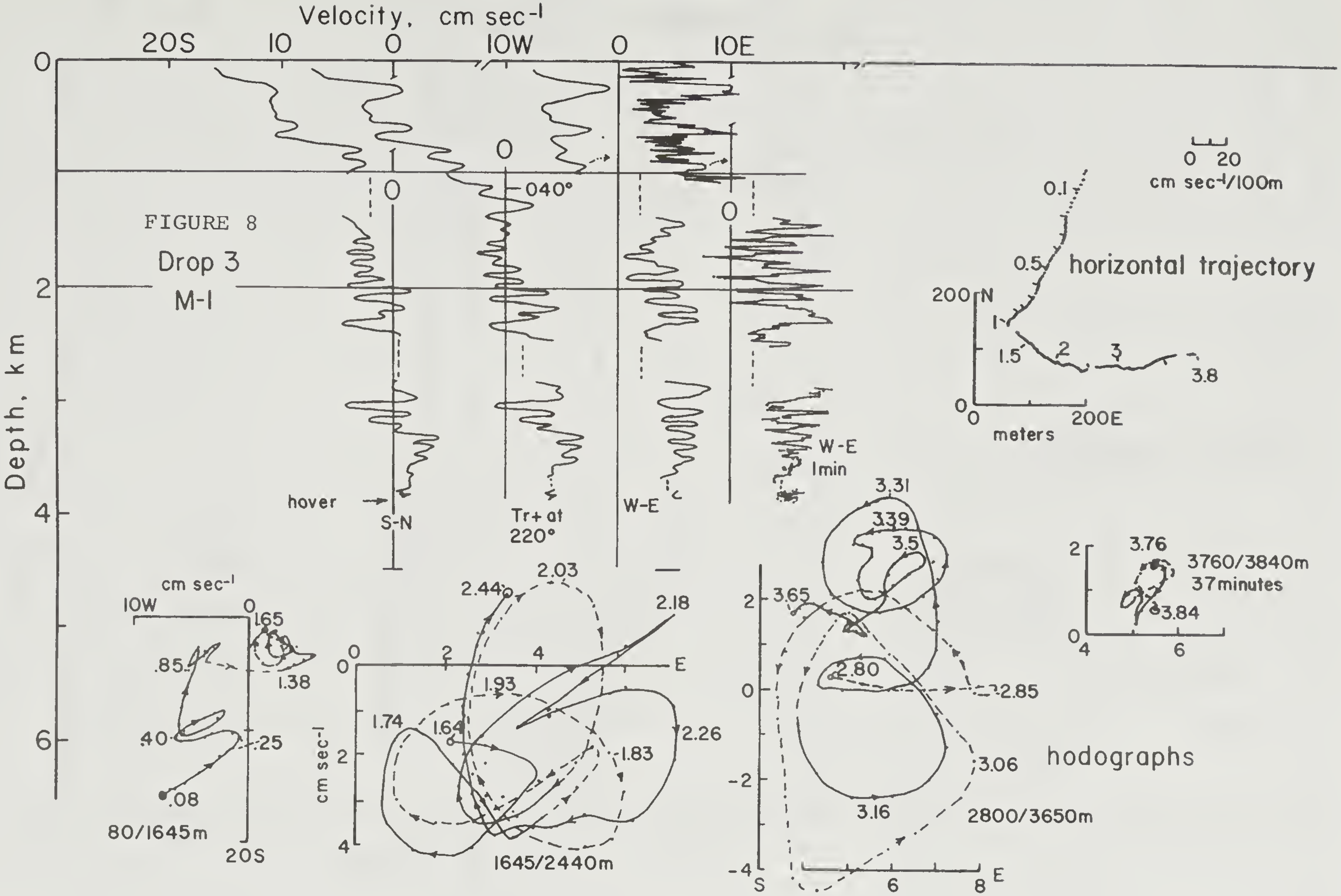


FIGURE 8
Drop 3
M-1

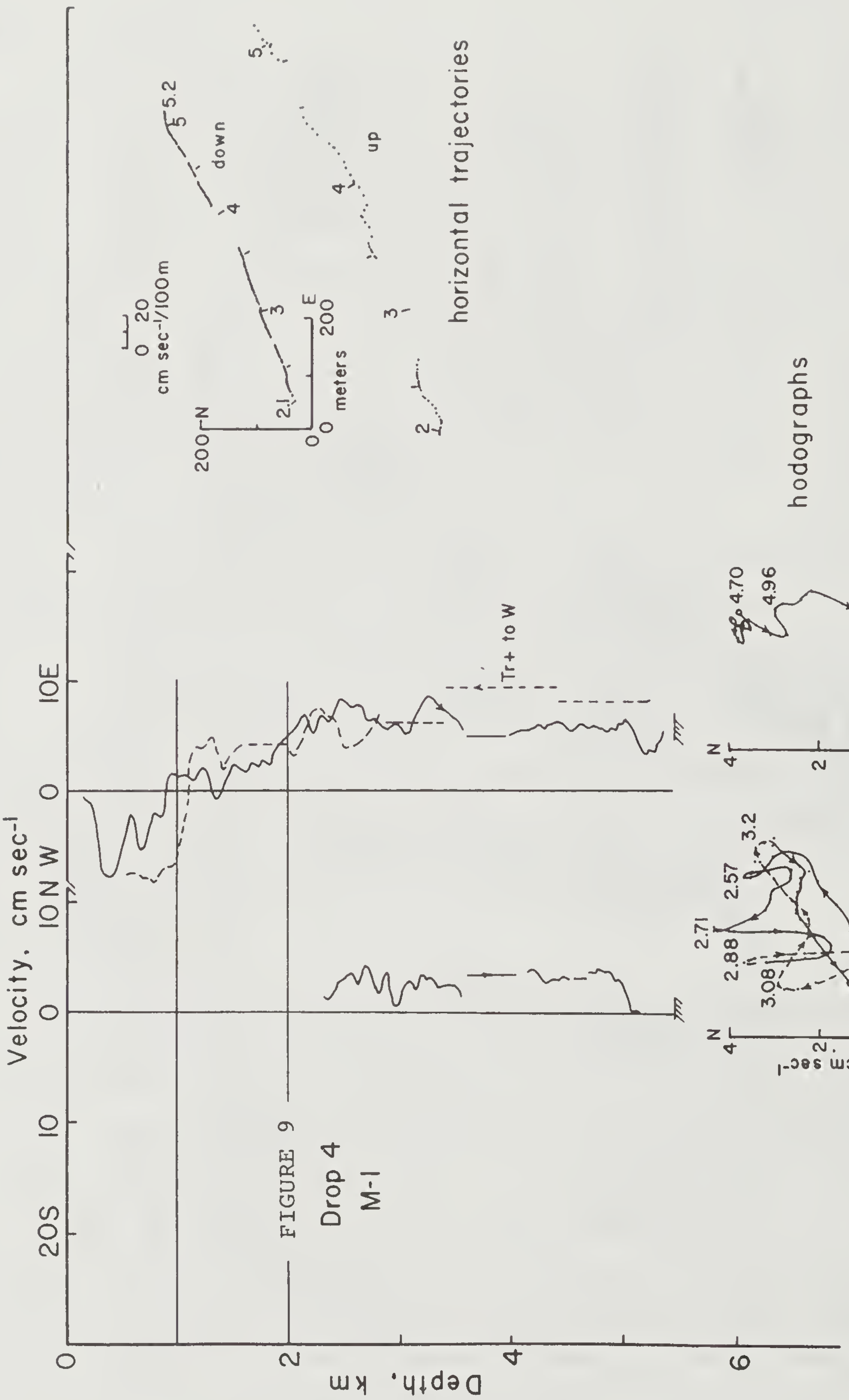


FIGURE 9

Drop 4

M-1

obtained yielded a trajectory which compares in shape with that obtained on the way down.

Drop 6, Fig. 10.

No choice of drop position over the array used in the previous drops was free of foreign transponder interference and so a third transponder, Tr 50, was added to the array at a location 7 km south of Tr 70, as shown in Fig. 1. Drops were continued now in the new array formed by Tr 50 and Tr 70. Tr 90 was far enough away for it to respond only infrequently.

The improvement in the performance of the system is apparent in the results for Drop 6 shown in Fig. 10.

Drop 7, Fig. 11.

The up profile of Drop 7 has poor resolution because the ascent velocity, 56 cm sec^{-1}, was too large for the unstreamlined aspect of the rising profiler and extraneous fluctuating horizontal velocities probably were introduced. Nevertheless, the velocities at small wavenumbers are consistent with those obtained during the descent.

Drop 8, Fig. 12.

For Drop 8 the float was trimmed to be just a little heavier than neutrally buoyant at the sea floor. The purpose, in part, was to obtain as slow a descent velocity as possible at great depths and so to obtain as high a vertical resolution near the floor as obtainable from the equipment.

The 1-min data at 4000 m was formed over 11 m steps and that length fell to 7 m at 5000 m. These data show high frequency current noise spikes in a band $\pm$ 1 1/2 cm sec^{-1}

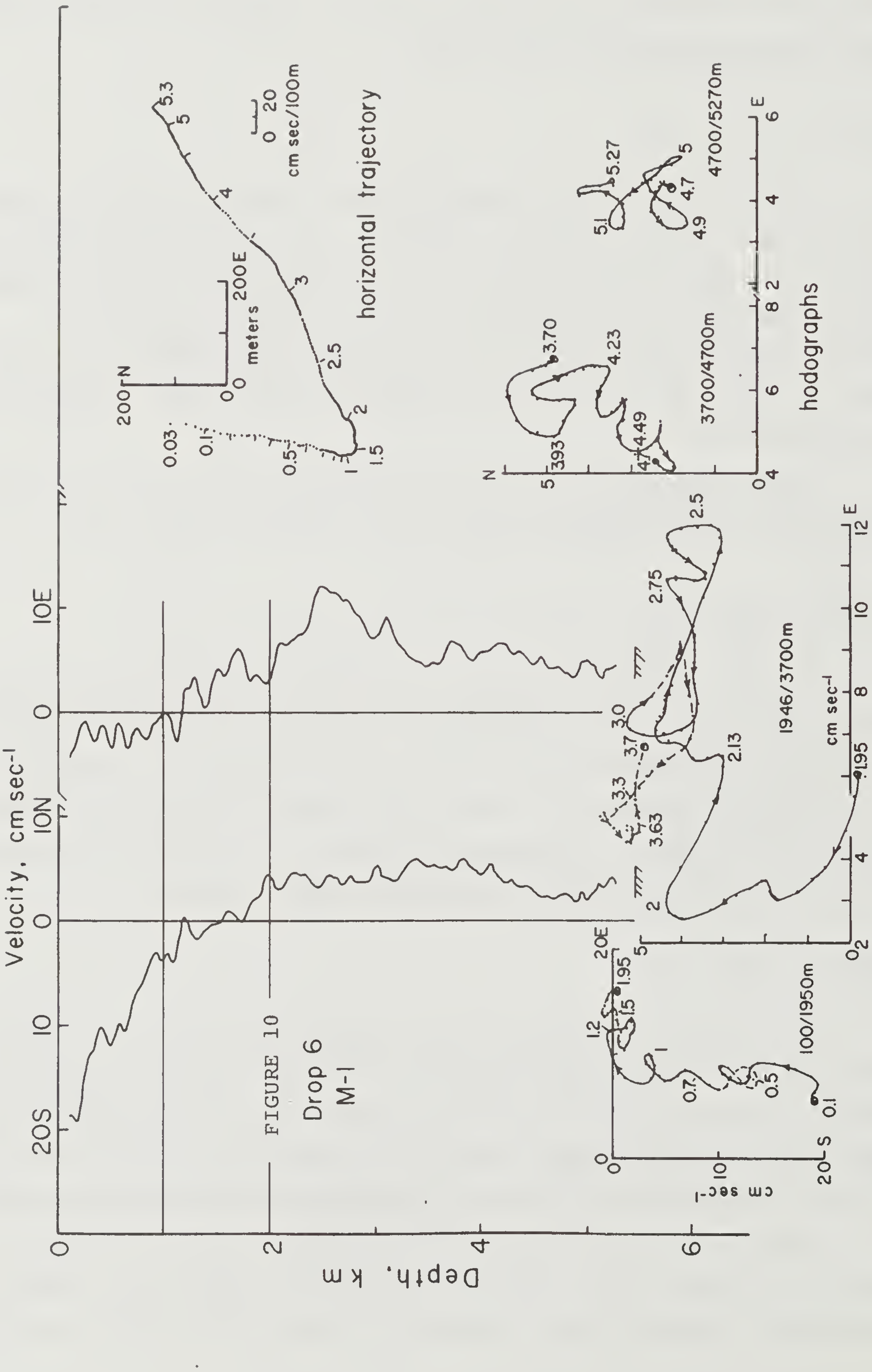


FIGURE 10
Drop 6
M-1

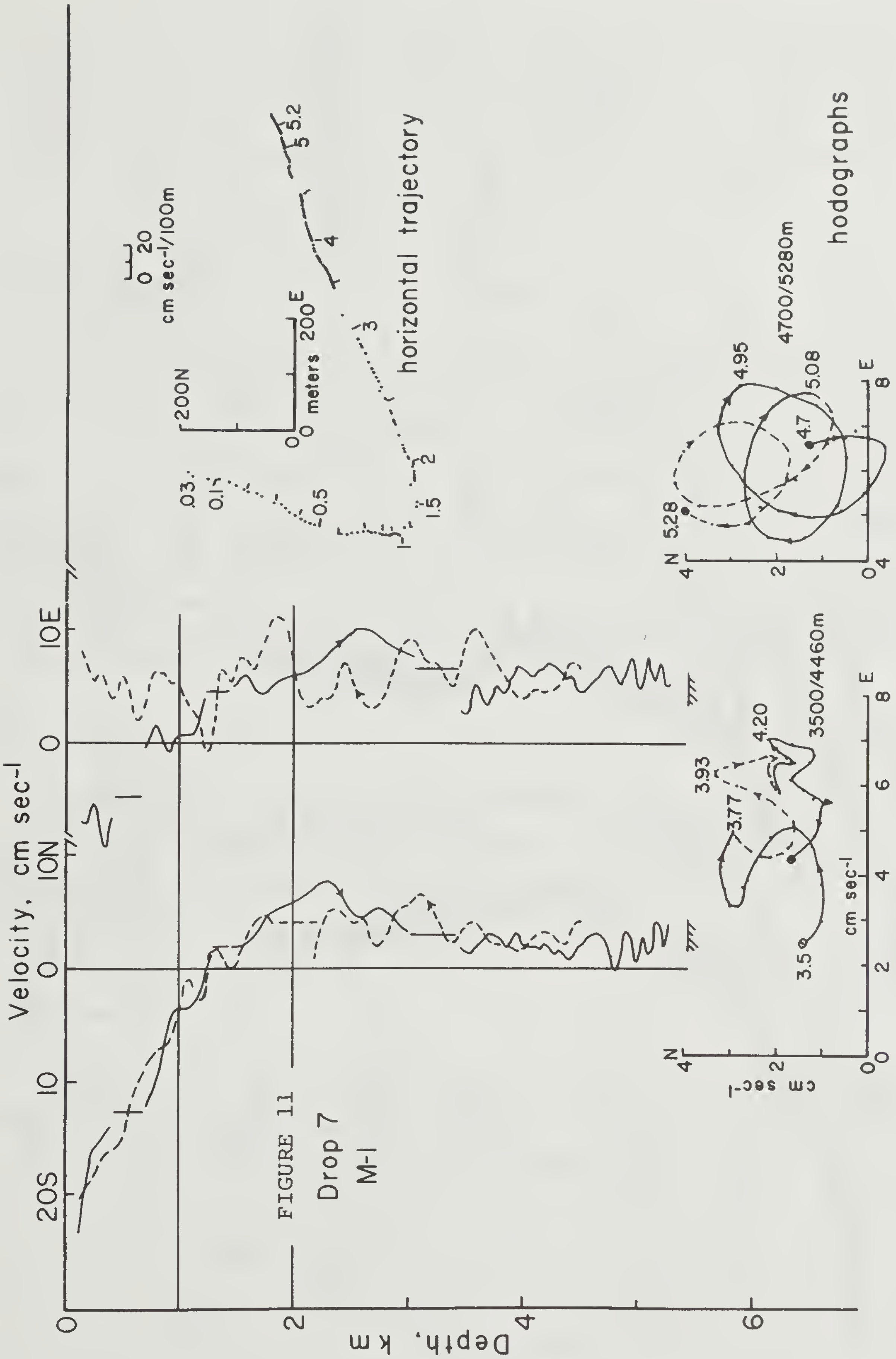


FIGURE 11
Drop 7
M-I

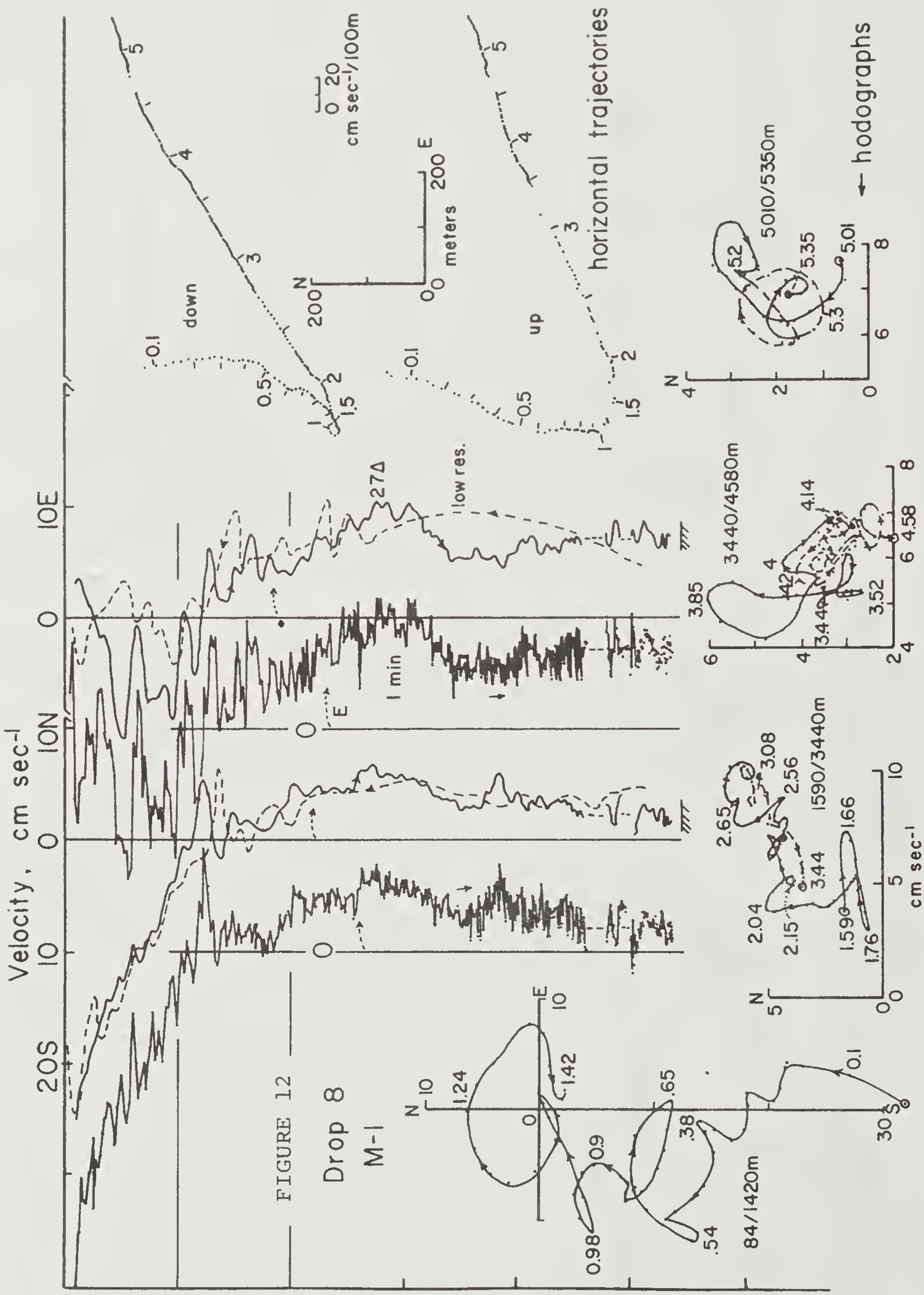


FIGURE 12
Drop 8
M-1

wide and these are considerably attenuated after filtering. The down and up results are similar except for some out-of-phaseness of the current fluctuations and some important shifts in the shapes of the trajectories near a depth of 1500 m. The time difference at 1500 m was 18.7 hr.

Drop 9, Fig. 13.

Drop 9 was another run set for the profiler to hover, this time at a depth of 5212 m. Data reduction was difficult because the hydrophone in the profiling float responded to a noisy release clock and so caused pings to be sent every 1/2 sec. For this reason, 2-min rather than 1-min averages were used as basic data points on the way down but 1-min averages were used for the ascent. The time difference at 4000 m between ascent and descent was 14.3 hr.

Drop 10, Fig. 14.

Good data was obtained in Drop 10 down to 4300 m. Below that, acoustic transmissions were poor during the descent but they improved during the rise which took place 15 hours later at 5000 m depth.

Drop 11, Fig. 15.

Drop 11 was made with the float set to hover at the relatively shallow depth of 2200 m. Again, one of the aims was to reduce the descent velocity so as to obtain a higher vertical resolution. Now the drop was made only slightly to the west of a line joining the transponders. Below a depth of 1000 m the float motion was toward that line. As a result, errors in the telemetered distances were considerably magnified in the E-W component determinations. On the

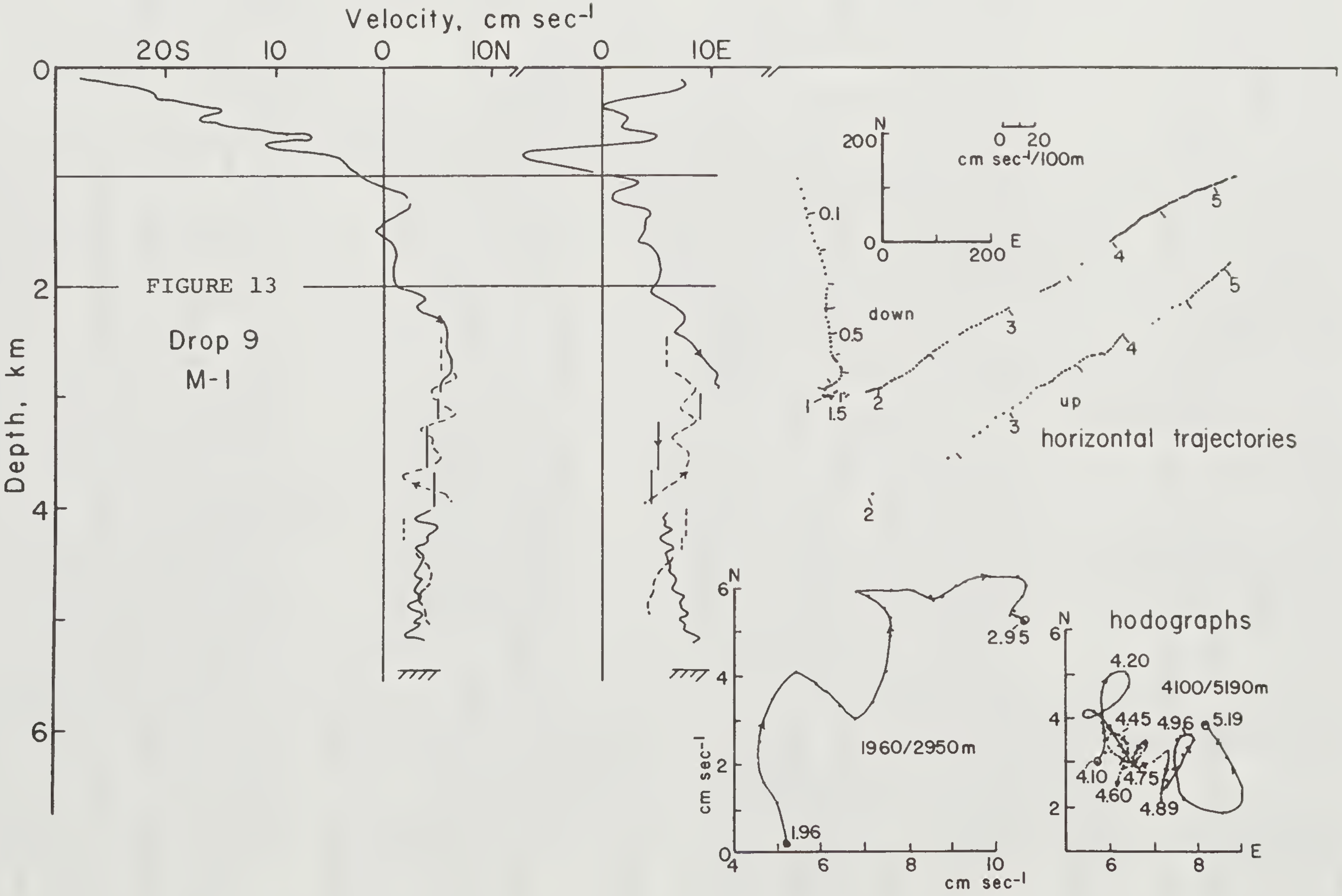


FIGURE 13

Velocity, cm sec^{-1}
20S
10
0
10N
0
10E
Depth, km
0
2
4
6
Drop 9
M-1
N
200
0
0
200
E
0 20
cm sec^{-1}/100m
0.1
0.5
1
1.5
2
3
4
5
down
up
horizontal trajectories
hodographs
1960/2950m
1.96
2.95
4100/5190m
4.20
4.45
4.96
5.19
4.10
4.75
4.60
4.89
cm sec^{-1}
4
6
8
10

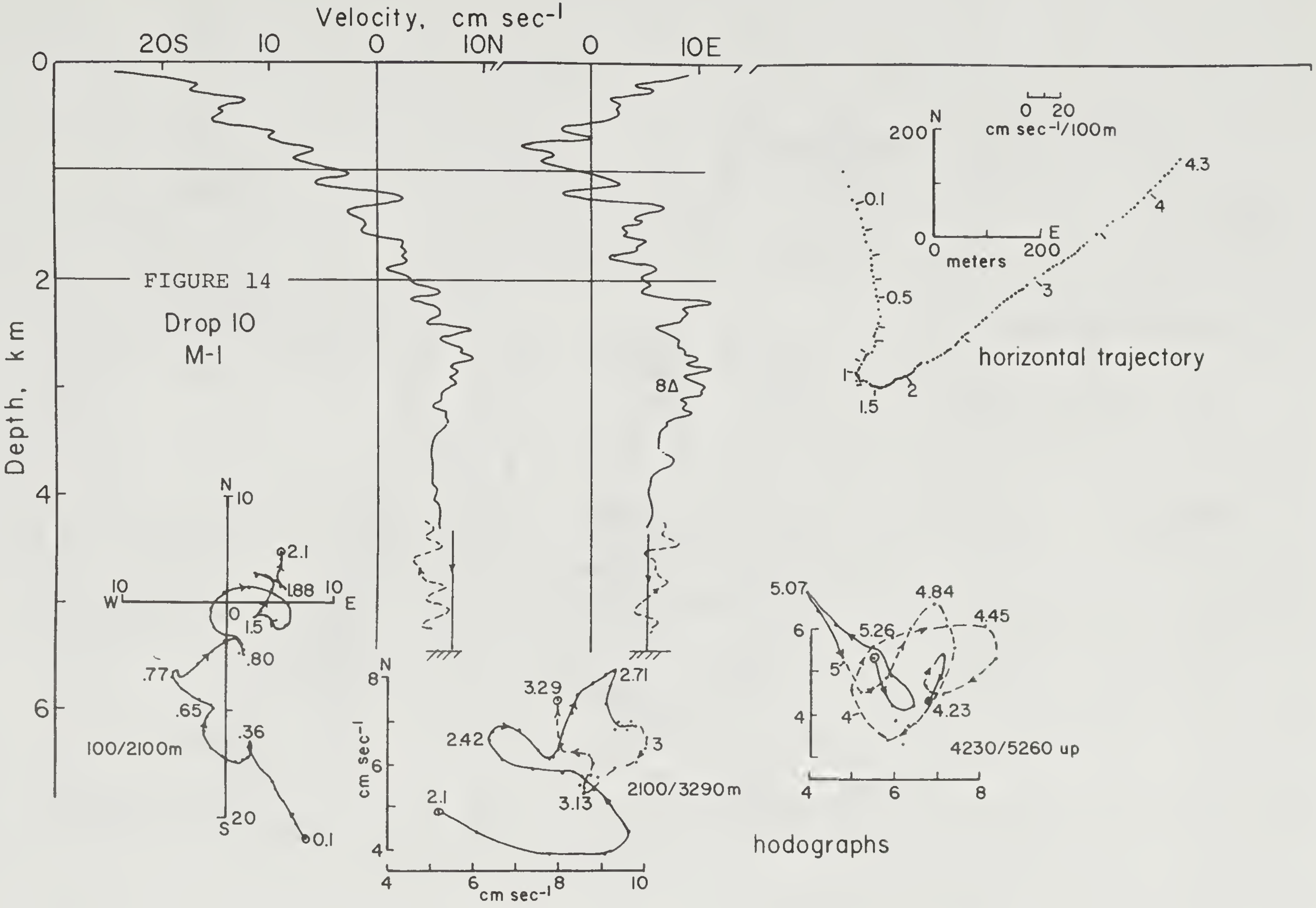


FIGURE 14

Drop 10
M-1

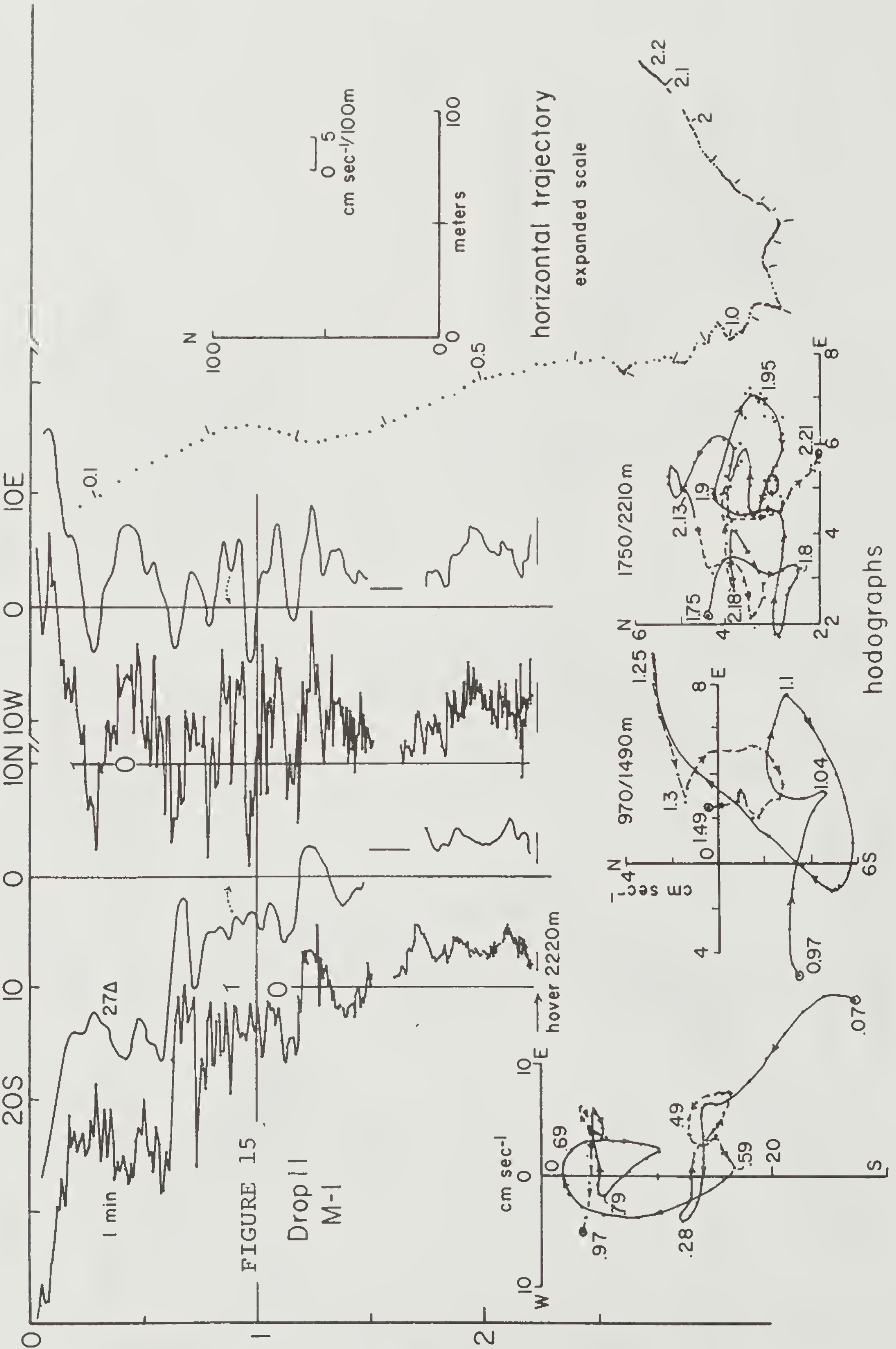


FIGURE 15

Drop 11
M-1

other hand, the large-wavenumber spikes of the 1-min data in the N-S direction are unusually small, in part because accuracy is helped here by averaging transmissions between the two transponders.

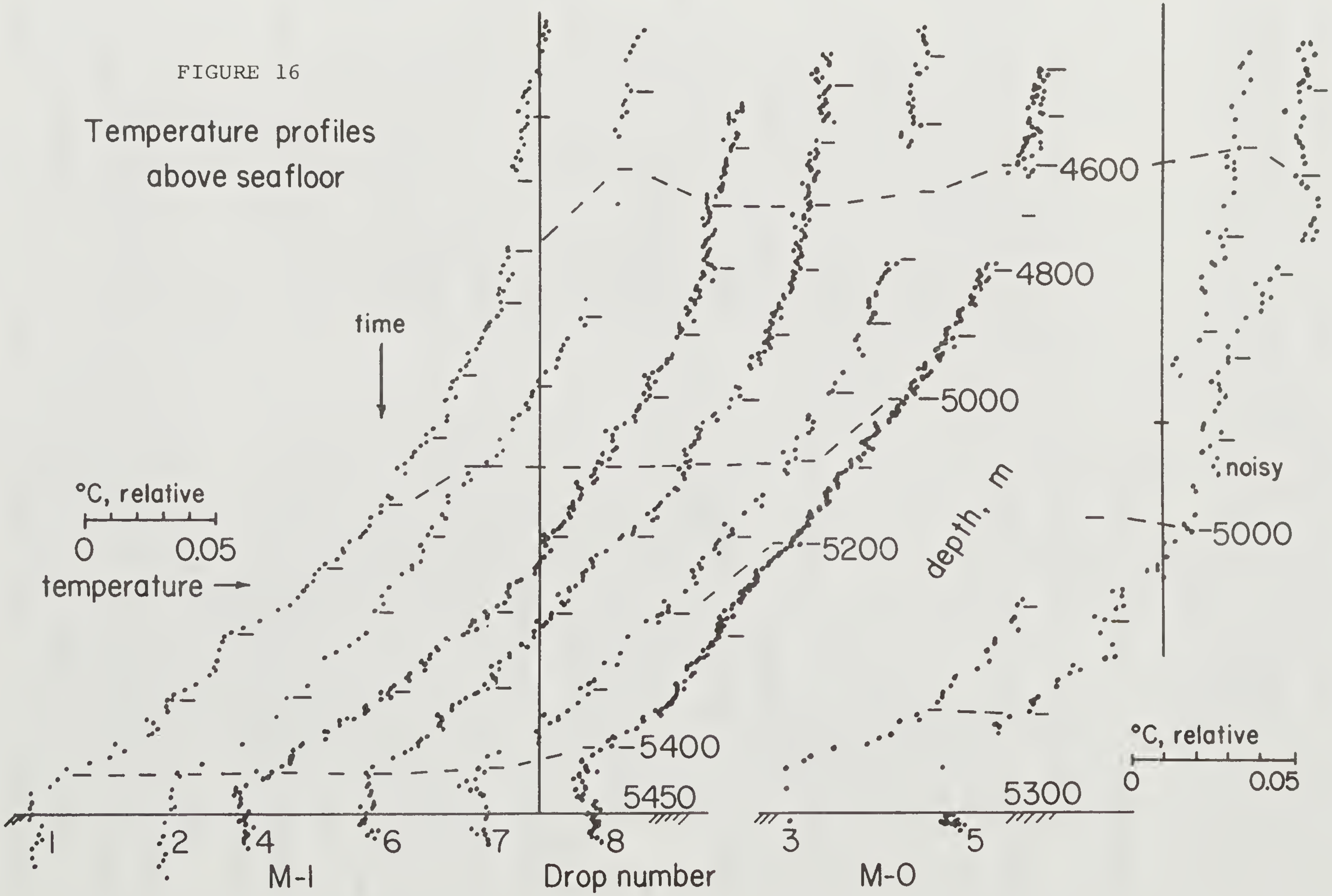
Temperature profiles, Fig. 16.

Temperature measurements of high sensitivity were desired for the waters below the main thermocline and these are most easily obtained by limiting the temperature scale to be in the range 1°C to 6°C. The resolution achieved is 0.001°C. Above a depth of approximately 1200 m, temperatures are off scale. Of particular interest at these locations are the temperatures close to the sea floor and the manner of change of these temperatures upwards towards depths near 4500 m where there is a temperature minimum in the M-1 area. Results are shown in Fig. 16. Here, points were obtained from individual temperature-doublet pulses transmitted approximately twice per minute. Because the temperature changes rather than true values were of primary importance, no attempt was made to apply corrections to the nominal values received. Relative temperatures are plotted as a function of time of descent and depths are marked at the appropriate times along the profiles. The average temperature at the floor was 2.14°C during M-1 and temperatures at other depths can be determined from this by means of the reference scale shown. Temperatures obtained during M-0 were of lower quality.

The presence of an isothermal bottom layer approximately 50 m thick is evident on all profiles, as is a relatively large gradient on top of this layer which decreases to near zero values at a depth of 4500 m. Temperatures marked below the line denoting the sea floor were obtained

FIGURE 16

Temperature profiles above seafloor



at various times while the float remained suspended 1.5 m above the sea floor.

CONCLUSIONS

The acoustic ranging scheme has shown its usefulness for determining transport and absolute currents as a function of depth and providing hodographs as well as for determining the vertical temperature structure and relating it to the current structure. The instrumentation, as used, is still in a relatively primitive form and can be developed in several directions. On the one hand, higher resolution and easier data reduction can be achieved if a tape recorder is placed in a profiling float. On the other hand, less resolution may be acceptable, as seems reasonable for most oceanographic purposes, and this can be achieved by means of considerably simpler and less expensive instrumentation. A desirable accuracy can be achieved in determining small wavenumber transport and current profiles in rapid drops with less elaborate and disposable instrumentation. Such data can be recorded by listening directly to acoustic transmissions in the drop area or by relaying the acoustic signals by means of radio to a nearby ship or vessel of opportunity in transit.

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Measurements of the transport and temperature as a function of depth were obtained at two locations in the North Atlantic during the MODE experiments of the IDOE. Vertical profiles of the current as well as hodographs were determined from these. Acoustic ranging was used for the flow measurements based on techniques developed in the instrumented float program of the senior author. The results of these measurements are presented in

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graphical form for experiments at 28°N, 68.7°W during a 4-day operation in 1972 and at 27.9°N. 69.7°W for a 11-day sequence in 1973. Profiling drops are described individually along with experimental or analytical factors affecting specific profiles. This report is a distillation of the measurements only and avoids interpretations of their significance.

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